Kinematics of Gas Near the Galactic Center

The number of similarities between the nuclei of some ordinary galaxies and the quasars, radio galaxies, and Seyfert nuclei has become impressively large. Ambartsumian's[1] recent account of the resemblances makes it hard not to believe that these energetic objects are galaxies passing through a difficult age, or perhaps suffering a not-so-rare galactic malady. And very few would deny that to understand this exceptional behavior it would be well to know how normal galaxies function in their innermost regions.

An example of what might be called a mild symptom of such manic behavior in a normal galaxy is the flow of gas outward from the central regions of our own galaxy. This phenomenon is not understood and its origins remain mysterious, but at least knowledge of the pattern of the flow is growing rapidly and it appears more and more certain that the flow originates in or near the galactic nucleus. Here we wish to summarize recent developments in the observational studies of the flow and mention some possible kinematic conclusions that may tentatively be drawn from them.

Our knowledge of gas motions near the galactic center comes chiefly from 21-cm and molecular radio frequency lines, though presumably there is much to learn from other radiation such as radio recombination lines. The first detailed 21-cm studies of gas near the galactic center were those of Rougoor and Oort (1960) and Rougoor.[2] Among their findings, that most clearly related to the galactic center is the discovery of high velocity† gas (200–250 km/sec) at both positive and negative longitudes‡ within 4° of the galactic center. These motions are consistent with the existence of a rotating disk in the center of the galaxy, situated in the galactic plane with radius ~ 750 pc and containing $\sim 5 \times 10^6 M_\odot$ of neutral hydrogen.

Rougoor found several other novel features possibly related with the galactic center. In the direction of the nonthermal radio source Sag A, itself

† Quoted observed velocities are all radial velocities with respect to the local standard of rest. Positive velocity indicates recession.

‡ Longitude increases in the counterclockwise direction as seen from above (north of) the plane and is zero at galactic center. The galactic rotation is seen as clockwise from this position. A length of 170 pc at the galactic center subtends 1° at the sun, which is the coordinate origin.

in the galactic center, he saw a strong 21-cm absorption line at a radial velocity of -53 km/sec. In the galactic plane, but away from the center, he was able to trace this line in emission from $l = -23°$ to $l = +6°$ where it became confused in the general galactic 21-cm emission. From this, Rougoor inferred the existence of a spiral arm at three or four kpc from the galactic center. This 3-kpc arm would be rotating at ~ 200 km/sec and expanding away from the galactic center at a speed of ~ 50 km/sec.

At positive longitudes Rougoor detected an emission feature at a velocity $\sim +135$ km/sec. This feature was taken to be a counterpart of the 3-kpc arm lying on the far side of the galactic center and likewise expanding. The 3-kpc arm and its counterpart—the so-called expanding arm—have HI masses about $10^7 M_{\odot}$ and $10^6 M_{\odot}$, respectively.

These observations have been thoroughly reviewed (Kerr,[3] Oort[4]) and Kerr has somewhat amplified Rougoor's picture. He pointed out the presence of some additional high velocity hydrogen near the galactic center which seems to be rotating in the same sense as the galaxy. The locus of this material is inclined to the galactic plane and Kerr felt that it was best described as a tilted bar-like structure interior to the 3-kpc and expanding arms. Kerr's picture of the central or nuclear disk was also a little more detailed. He proposed that the inner part just rotates, but that the outer part also expands slowly. Indeed, if one looks at the observations it seems possible to assign an expansion velocity of about 30 km/sec to the disk. Such an expansion may be related to a weak 21-cm absorption line seen against Sag A (Kerr and Vallak[5]) at -30 km/sec, though Kerr[3] has interpreted this absorption feature differently.

These studies left an impression of general outflow in spite of the existence in HI of weak positive velocity absorption in the direction of the galactic center. Observations of hydroxyl (OH) absorption near the galactic center (Bolton et al.[6]) forcefully underscored the importance of these positive velocity features. An intense OH absorption feature at about $+40$ km/sec was found in the direction of Sag A and, more recently, similar features have been detected (Zuckerman et al.[7]) in formaldehyde (H_2CO). If, as has been generally believed, the molecules are in front of Sag A, their spectra imply flow into the galactic center within the nuclear disk where there had been thought to be no radial flow, or possibly a weak outflow.

Extensive surveys of OH (Robinson and McGee[8]) and H_2CO (Scoville, Solomon, and Thaddeus[9]) have now been carried out within several degrees of the galactic center. These have shown that the molecules are contained in as many as 60 discrete clouds. Although a few of these clouds apparently lie in the 3-kpc and other arms, most of them show broad lines, have high radial velocities, and lie in a thin ($\frac{1}{2}°$) layer aligned with the galactic plane and extending roughly 2° in longitude about the galactic center. The extraordinary clouds producing these broad lines are probably located within the nuclear disk; several have densities $\gtrsim 10^3$H/cc with individual masses up to perhaps $10^6 M_\odot$. The total mass in all these molecular clouds ($\sim 3 \times 10^6 M_\odot$) is comparable to the mass of neutral hydrogen of the nuclear disk. Roughly half of these clouds show "forbidden" velocities in the sense that if they simply rotated about the galactic center the implied sense of rotation would be contrary to that of the nuclear disk and the galaxy. The velocities of the other clouds bear no obvious relation to what might be expected for the motion of the nuclear disk in which they are presumably embedded.

These observations begin to show how the molecular studies can complement the 21-cm observations. They have the advantage of leading to kinematical data for dense low velocity gas near the galactic center which could not be detected in 21-cm because of the galactic background. In this way high velocity features can be traced to low velocities, at least if the velocity pattern is not too complicated.

But complications are becoming the vogue in this subject and the 21-cm results have been contributing their share. A recent survey of 21-cm emission outside the galactic plane, yet near the center, also shows forbidden velocities (Van der Kruit[10]). Motions were seen in the two quadrants on the sky where Kerr and Sinclair[11] found enhanced continuum emission at 20 cm and which, they suggested, comes from jets of gas ejected in opposite directions from the galactic nucleus and well away from the plane. However, Van der Kruit's features, some of which had already been found by Shane, are generally much farther from the galactic center than the continuum ridges and do not necessarily provide strong evidence for highly directional expulsion. On the other hand, there are fainter 21-cm features at velocities of $\pm$ 150 km/sec which coincide with the continuum ridges (Sanders, Wrixon, and Penzias[12]).

Van der Kruit also found an extensive feature south of the plane at positive longitudes with velocities ranging from about -50 km/sec to -130 km/sec as the longitude decreases to zero. Further observations with high sensitivity (Sanders et al.[12]) show that this feature extends to a longitude of $-6°$ with negative velocities up to -160 km/sec and remains below the plane.

It is difficult to interpret all these findings kinematically, especially as they may arise from separate entities whose emission may overlap on the sky and give the impression of a single object. An example where this may have happened is given by Simonson and Sancisi[13] and Mader[14] who studied the expanding arm at positive longitude. They have shown that this feature, previously considered a single arm, in its latitude distribution gives the impression of two separate entities. One of the two components extends from the galactic center to longitude 13°, has a velocity $+135$ km/sec at $l=0$, and is somewhat above the plane. The other component, which is very close to the plane, has been traced from longitude 22° to 3° and its extrapolated velocity at 0° is $+50$ km/sec. Mader suggests that this latter, outer component is the true counterpart of the 3-kpc arm since it has about the right expansion velocity and angular extent.

What then are we to make of the inner component of Mader, and Simonson and Sancisi which was previously thought to be part of the expanding arm? It has positive velocity ~ 135 km/sec and extends in longitude to 13°. Its longitude-velocity distribution is consistent with the interpretation that it represents an arm at $2\frac{1}{2}$ kpc from the galactic center, expanding outward at 135 km/sec and rotating at a speed of 170 km/sec (Sanders and Wrixon[15]). If this is a correct interpretation, then it is natural to enquire whether this "inner expanding arm" has a counterpart on our side of the galactic center. Such a counterpart should have the appropriate negative velocity and longitude distribution, and the extensive feature south of the plane observed by Van der Kruit[10] seems to fit these requirements (Sanders and Wrixon[15]). Thus, there may be arms on each side of the galactic center, or possibly a single ring around the center, at radius $\sim 2\frac{1}{2}$ kpc and expanding at 135 km/sec. The plane containing these inner expanding arms, or ring, is slightly inclined to the galactic plane as is indicated by the latitude distribution.

Such smooth-flowing features may not give an exact picture but they do represent some main features of the observations. A similar simplification can be made for the molecular case (Scoville[16]). Most of the molecular clouds producing broad lines within $l = \pm 2°$ may be connected up into a single, irregular, elliptical feature in longitude-velocity diagram. This distribution may be qualitatively accounted for by a ring around the galactic center of radius 250 pc, rotating at 50 km/sec and either expanding or contracting at a speed of ~ 100 km/sec. Here we must allow for the possibility that though the clouds are seen in absorption they need not be situated in front of Sag A. The Sag A complex has many components and some of these may be HII regions located on the far side of galactic center.

Though the picture of the ring of molecular clouds expanding or contracting rationalizes somewhat the observed molecular velocities, it still leaves open the problem of the connection with the nuclear disk. The low rotational velocity of the ring is consistent with the picture that it is expanding, or falling back after an earlier expansion. One can find some evidence for high velocity hydrogen just outside the postulated ring and it could be that the ring is expanding and carrying the disk material with it. At the estimated velocity of 100 km/sec shocks might be produced and lead to the formation of extensive diffuse HII regions. Thus, radio recombination lines might help to unravel part of this problem. Nevertheless, it seems that between the suggested expanding rings at radii 250 pc and $2\frac{1}{2}$ kpc there is the nuclear disk—or perhaps we should say annulus—with very little expansion.

It remains puzzling that the nuclear disk exists in its present apparent state of non-expansion. Perhaps this conclusion can be mitigated by considering models with non-axisymmetric velocity fields for the nuclear disk, as would seem to be called for by the recent studies of analogous flows in Andromeda by Rubin and Ford (1971). But until such possibilities are fully explored, we probably should try to understand the model as it stands. Perhaps, as Oort[4] suggests, the disk represents matter that has fallen back from a previous expulsion and has already dissipated its kinetic energy. There may have been enough time for this in the 5 million years since the $2\frac{1}{2}$ kpc ring went off. Alternatively, there may be a continual gentle outflow of matter which replenishes the disk between the events producing the rings. This picture would require some nonradial force to explain the relatively rapid rotation of the disk and magnetic fields might work to this end (e.g., Mestel, Moore, and Spiegel[17]). However, the rotation rate of the disk agrees reasonably with that of Andromeda and also with the circular velocities computed for the mass distribution derived from the ir emission near the center of the galaxy (Lowinger and Sanders[18]). This seems too great a coincidence. In short, in the obvious mechanisms for the outflow, the explanations of the apparent nonexpansion of the nuclear disk seem *ad hoc*. Despite this problem it seems reasonable to suppose that the expanding "rings" at 250 pc and $2\frac{1}{2}$ kpc and the 3 kpc arm provide evidence for material ejection from the galactic nucleus in discrete, mildly energetic events.

The molecular ring and the $2\frac{1}{2}$ kpc ring have expansion energies of about 5×10^{53} ergs at present. What the total energy would be in such events is uncertain but, from various points of view a factor of 10 or 10^2 over this quantity might not be outlandish. A somewhat larger total energy ($\sim 10^{56}$ erg) would be called for if the 3 kpc arm and its counterpart were caused to move outward by matter expelled in a previous similar event. (But other interpretations have been considered (Lin and Shu[19], Shane[20]).) It is also worth noting that unless the molecular ring is presently being driven, it will not escape from the galactic center, especially as it must be sweeping up matter in the disk. If we assume that it has swept up all the matter in its path, using the conventional disk model, we can estimate its intrinsic angular momentum. For the extreme case in which no torques are exerted, we find that much of the mass of the ring came from within tens of pcs of the galactic center.

This three-ring model of outflow in the plane raises the mass problem that was formerly only associated with the picture of a quasi-steady outflow. On the assumption that these rings are evidence for expulsion from the center, we find that events causing them occurred about 10^7, 5×10^6 and 10^6 years ago. Thus the postulated events that produce the expanding rings seem to have been spaced in time by 5×10^6 years, with an ejection in the plane of about $10^6 M_\odot$ on each occasion. If the events recur at this rate over the life of the galaxy, the total gaseous outflux would be uncomfortably large. If there is even more ejection out of the plane, the mass difficulty becomes quite severe.

Whether there is mass ejection out of the plane is rather difficult to ascertain from the observations. As Van der Kruit has stressed, one cannot even be certain whether the high velocities out of the plane imply outflow or inflow. An inflow from out of the plane would help to alleviate the mass problem (Moore and Spiegel[21]), and perhaps some of the diffuse matter out of the plane is falling in. But it is hard to believe that the jet-like structures indicated by the HI and continuum ridges are not being shot out of the nucleus, and on balance there does seem to be a serious mass problem.

If the HI ridges do indicate ejection out of the plane, they also shed some light on its nature. The velocity of the HI ridges seems approximately constant with latitude, and we might surmise that this indicates more or less steady, directed outflow which has lasted for about 5×10^5 years. Thus, the jets could well have been initiated in the event that produced the expanding molecular ring, and they seem to have persisted ever since. Their total HI mass is $\sim 5 \times 10^4\ M_{\odot}$ and their kinetic energy $\sim 10^{52}$ erg, neglecting projection effects (Sanders and Wrixon[15]). This indicates a kinetic energy input rate $\sim 10^{39}$ erg/sec and a continual source of this strength could also produce the relativistic electrons needed for the nonthermal radiation from Sag A.

It would of course be interesting as well to know how long such a presumed energy source can last. A fragment of evidence may come from the center of Andromeda which is presumably like our own galactic center in its kinematics (Rubin and Ford 1971). However, no nonthermal source has been detected at the center of Andromeda. If Andromeda is indeed like our galaxy and there is really no nonthermal source, we might conclude that the source powering the nonthermal component of Sag A, the jets, and the other seemingly related emissions (Burbidge[22]) are operating only intermittently (unless the nonthermal radiation is beamed). That is, the source is turned on by an explosive event every 5×10^6 years or so but fades before the next one. However, it should last at least as long as $\sim 5 \times 10^5$ years, the presumed age of the jets. This provides a time scale related to the presumed central object, albeit a very unreliable one.

We hardly need to add, in conclusion, that the kinds of models that emerge from the velocity observations can have a measure of simplicity only when the outstanding features are taken out of context. The tendency to read order in chaos is evidently strong, but in many cases it seems to be a fruitful one. There is certainly much to be learned by a more thorough scrutiny of the observations, but even as things stand, a fascinating picture of the workings of the inner galaxy is emerging.

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